



Title	Formation and evolution of satellite systems
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Formation and Evolution of Satellite Systems

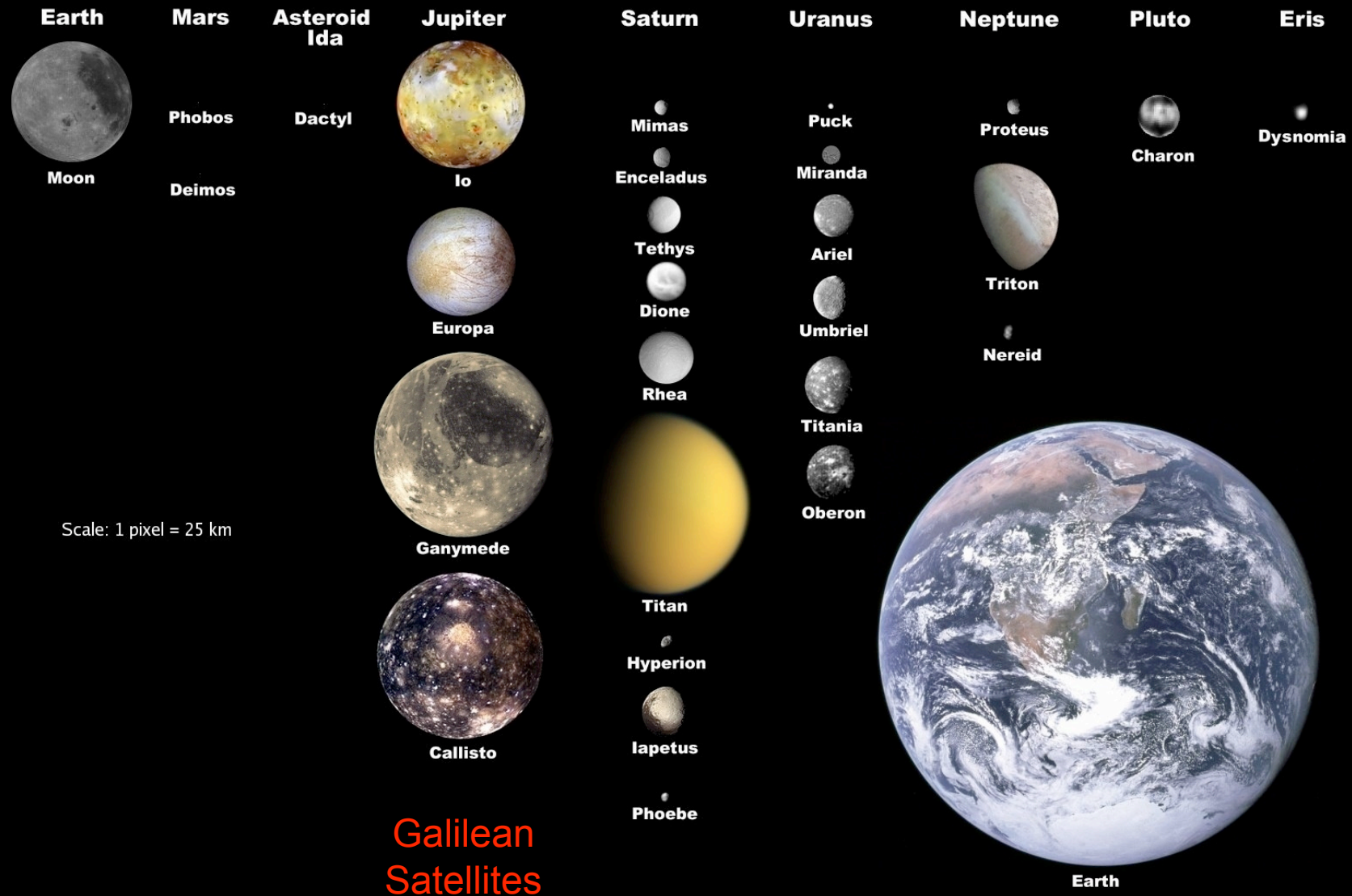
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Collaborators:

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W. H. Cheng (*HKU*), Stan Peale (*UCSB*)

Selected Moons of the Solar System, with Earth for Scale



Satellite Systems

- Regular satellites of Jupiter, Saturn, and Uranus:
 - Prograde orbits nearly coplanar with planet's equator plane.
 - a up to tens of R_p
 - $M_{\text{tot}}/M_p = 1.1 - 2.5 \times 10^{-4}$
 - Formation in circumplanetary disk
- Earth-Moon and Pluto-Charon:
 - $M_s/M_p \approx 1/80$ and $1/9$
 - $a/R_p = 60$ and 17
 - Pluto-Charon dual synchronous
 - Giant impact origin

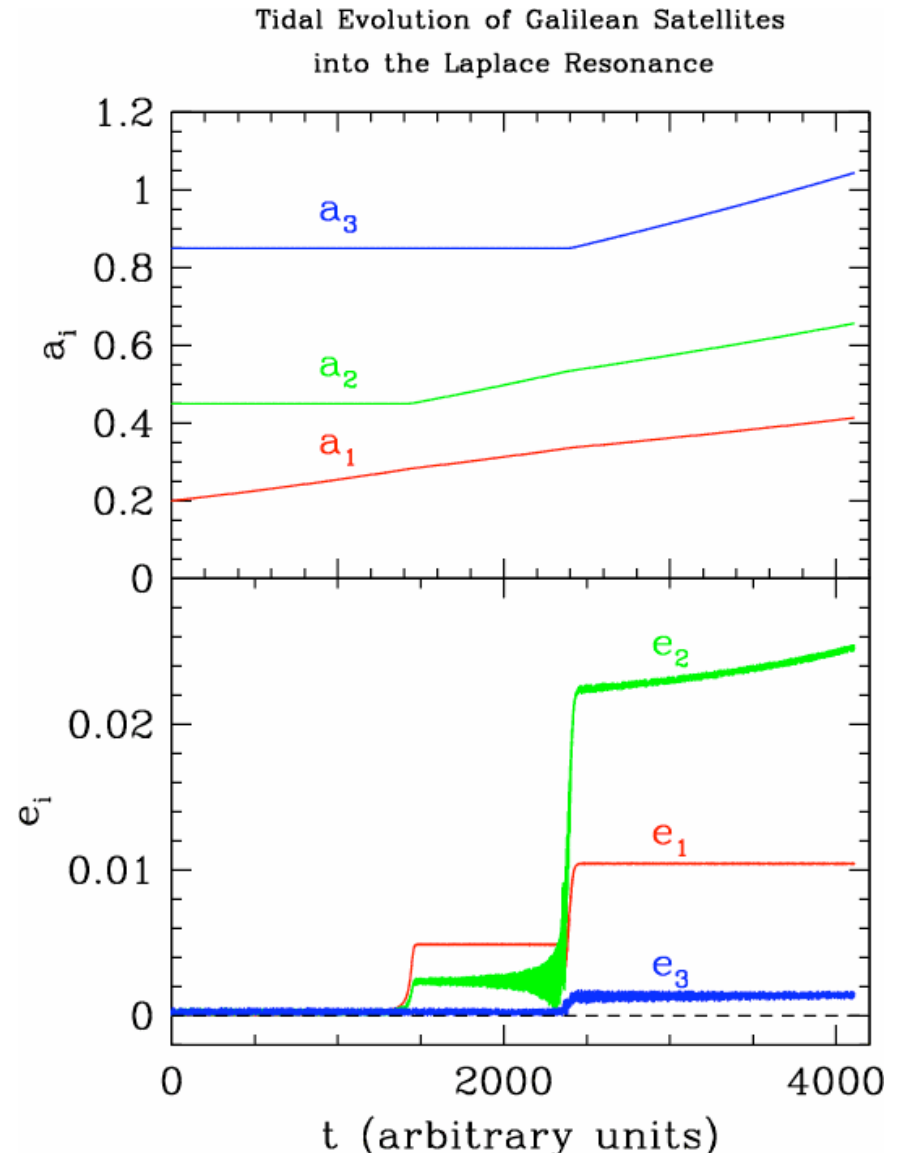
Formation of the Galilean Satellites

- Constraints:
 - Ganymede and Callisto about half rock and half ice.
 - Callisto only partially differentiated ($I/MR^2 \approx 0.355$; Anderson et al. 2001).
- Formation scenarios:
 - Gas poor planetesimal capture model (Safronov et al. 1986; Estrada & Mosqueira 2006).
 - Minimum mass subnebula model (Lunine & Stevenson 1982; Takata & Stevenson 1996; Mosqueira & Estrada 2003).
 - Gas-starved subnebula model (Canup & Ward 2002).

- Nature of mass and angular momentum transport in subnebula is a major uncertainty in modeling satellite origins.
- Turbulence driven by Magneto-Rotational Instability ([MRI](#)) provides transport if gas is sufficiently ionized to couple to the magnetic fields.

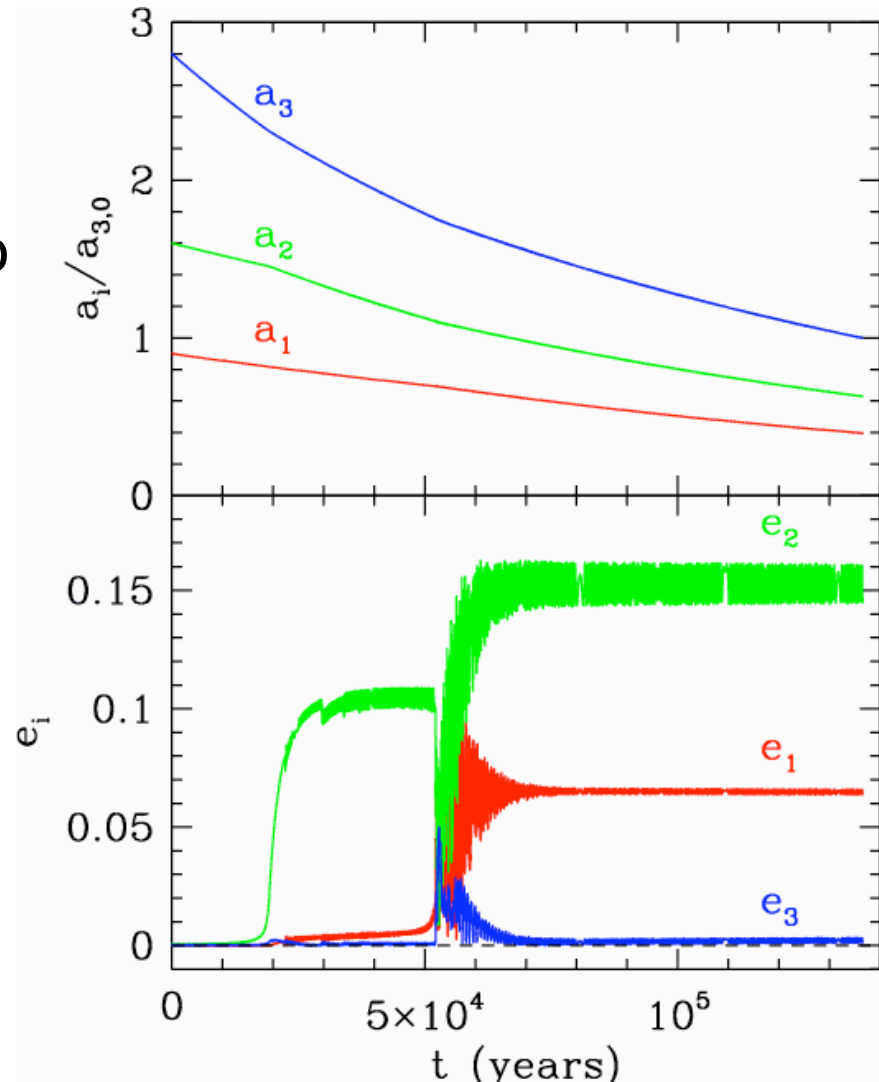
Origin of the Laplace Resonance: Tidal or Primordial?

- Orbits of Io, Europa, and Ganymede are in the **Laplace resonance**, with orbital periods nearly in the ratio 1:2:4.
- Resonances could be assembled **inside-out** long after the formation of the satellites by tidal expansion of orbits (Goldreich 1965, Yoder 1979, Yoder & Peale 1980).

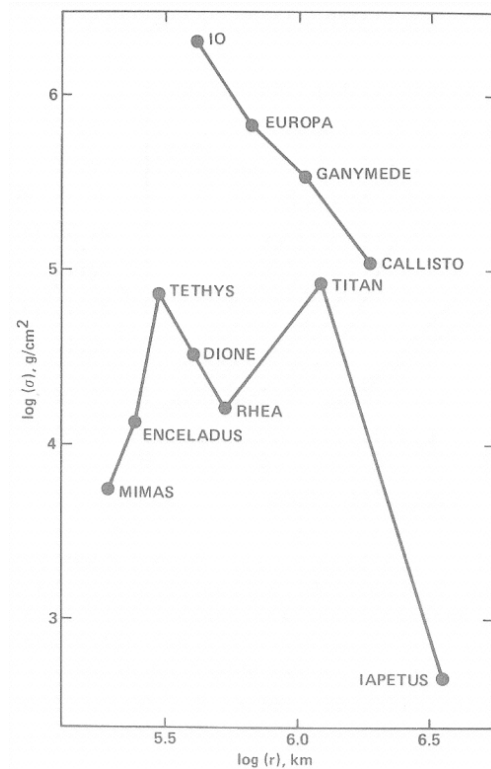


- Alternatively, resonances could be assembled **outside-in** during satellite formation by the differential migration of satellites due to interactions with circumjovian disk (Peale & Lee 2002; Sasaki, Stewart & Ida 2009).
- Probability of capture into the observed Laplace resonance could be sensitive to circumjovian disk model.

Nebula Induced Evolution of Galilean Satellites into Laplace Resonance

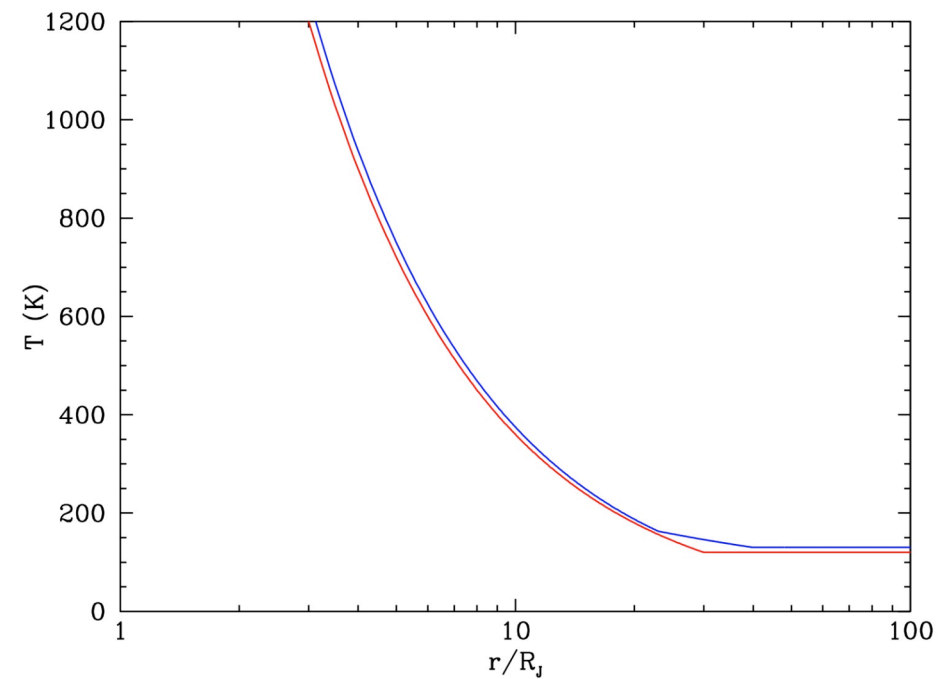
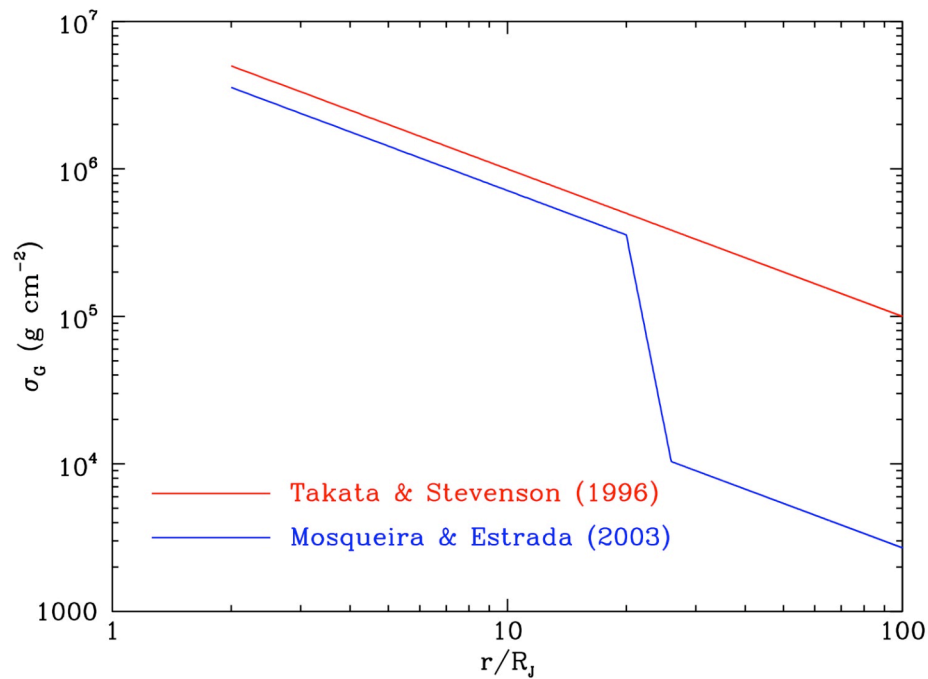


Minimum Mass Subnebula Model



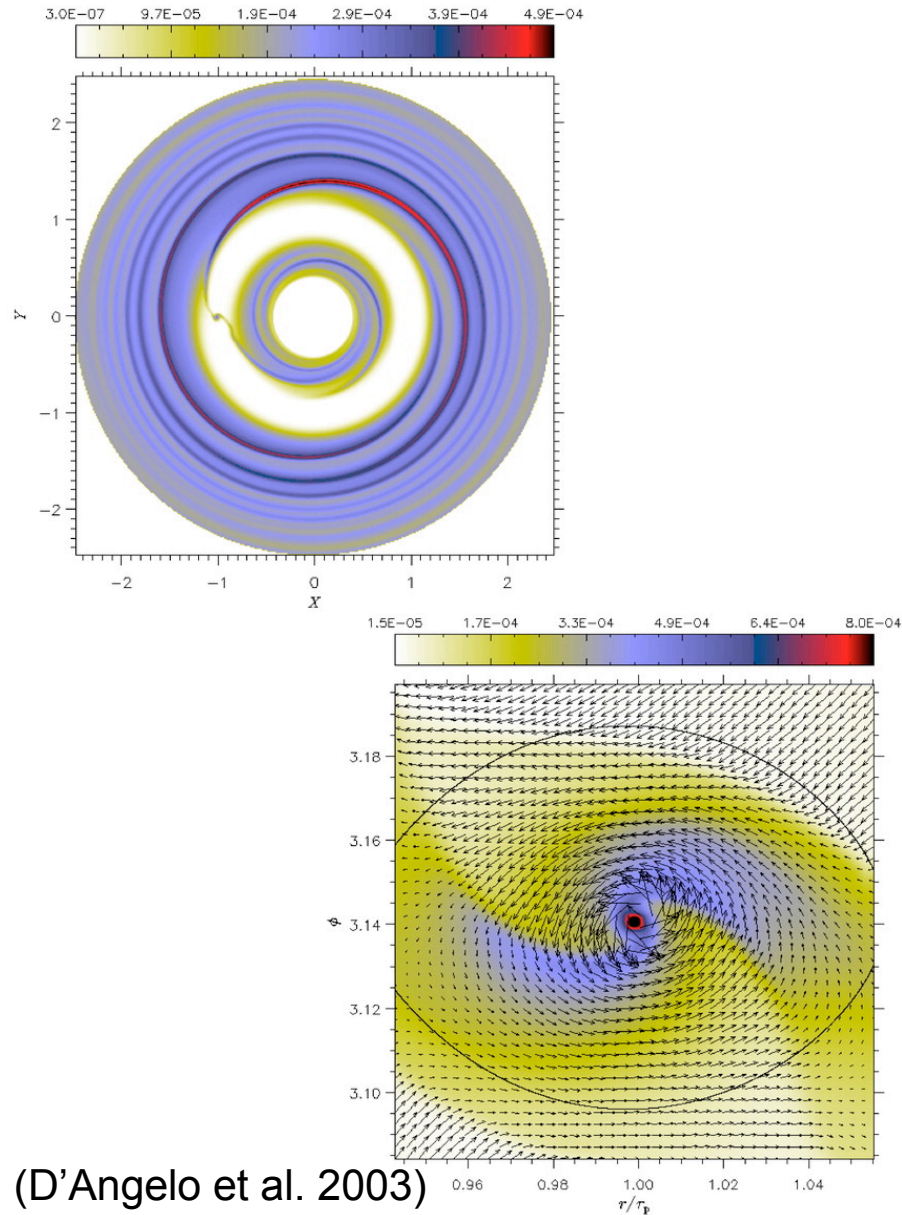
(Pollack & Consolmagno 1984)

- Analogous to minimum mass solar nebula.
- Galilean satellites + enough volatiles for Solar abundance.



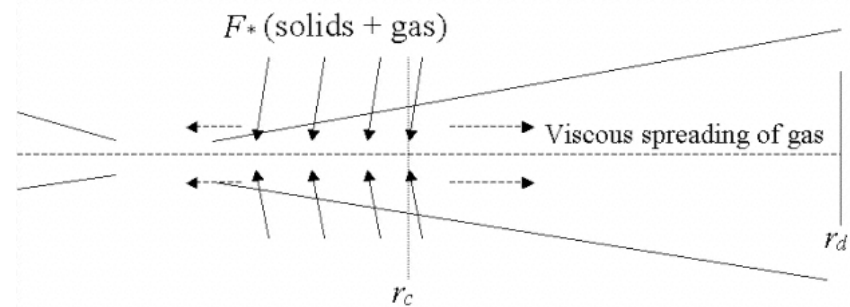
- Very high gas surface density $\sigma_G \sim 1/r$.
- Sharp drop in σ_G at $r/R_J \approx 23$ in the Mosqueira & Estrada (2003) model.
- Temperature $T \sim 1/r$ at $r/R_J < 30$ and \sim constant at $r/R_J > 30$.

Gas-starved Subnebula Model



(D'Angelo et al. 2003)

- Not all mass needed to form the satellites in the disk all at once.
- Replenished by slow inflow of gas and solids from the solar nebula after Jupiter opens a gap.

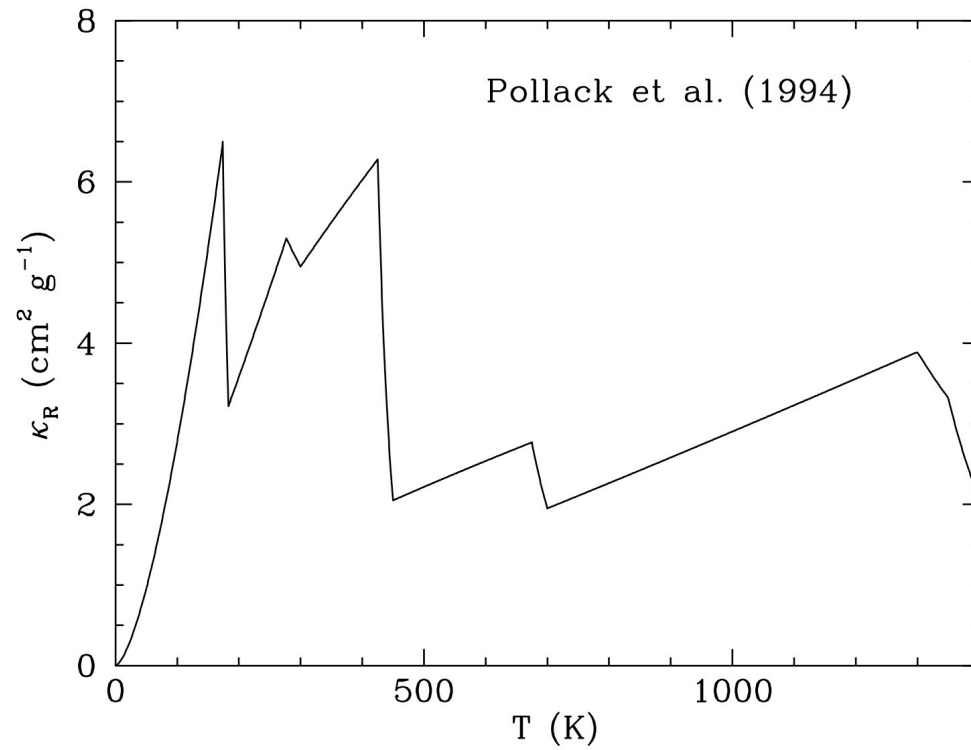


(Canup & Ward 2002)

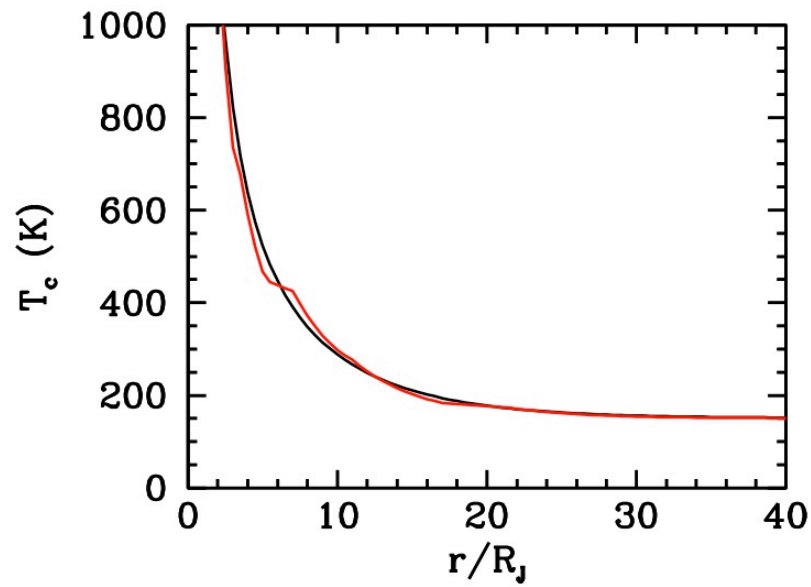
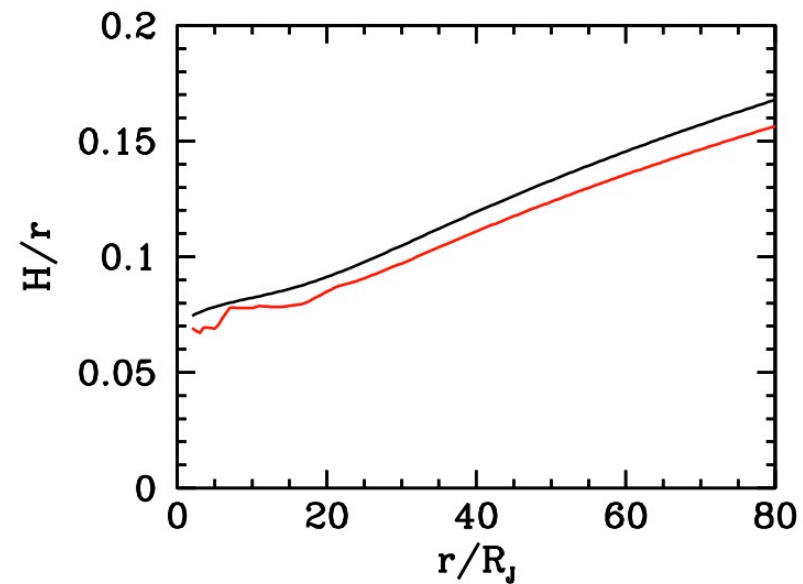
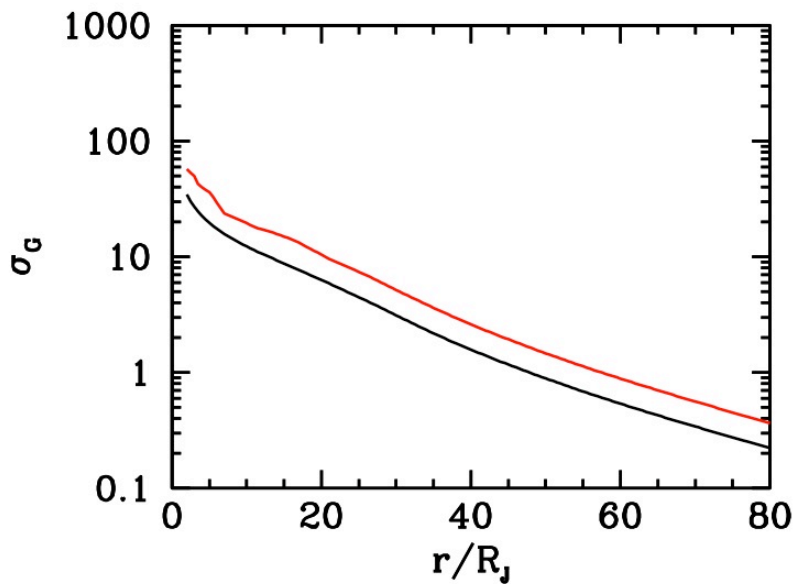
We have constructed Improved Gas-starved Subnebula models with

- Improved treatment of low τ_c (optical depth to the midplane) regime and incoming radiation of Jupiter.
- Midplane temperature T_c using
 - Analytic vertical structure model of Hubeny (1991) for viscous dissipation and isotropic solar nebula irradiation
 - Extension by Malbet et al. (2001) for irradiation by a central source (i.e. Jupiter).

$$T_c^4 = \frac{3}{4} \left[\frac{\tau_c}{2} + \frac{1}{\sqrt{3}} + \frac{1}{3\tau_c} \right] T_d^4 + T_{\text{neb}}^4 \\ + \frac{3}{4} \left[\mu_J (1 - e^{-\tau_c/\mu_J}) + \frac{1}{\sqrt{3}} + \frac{1}{3\mu_J} e^{-\tau_c/\mu_J} \right] \left(\frac{\mu_J}{2} \right) \left(\frac{R_J}{r} \right)^2 T_J^4,$$



- Opacity $\kappa = f_{\text{opac}} \kappa_P$, where κ_P is the Pollack et al. (1994) temperature dependent opacity and $f_{\text{opac}} \leq 1$.



- High opacity model:

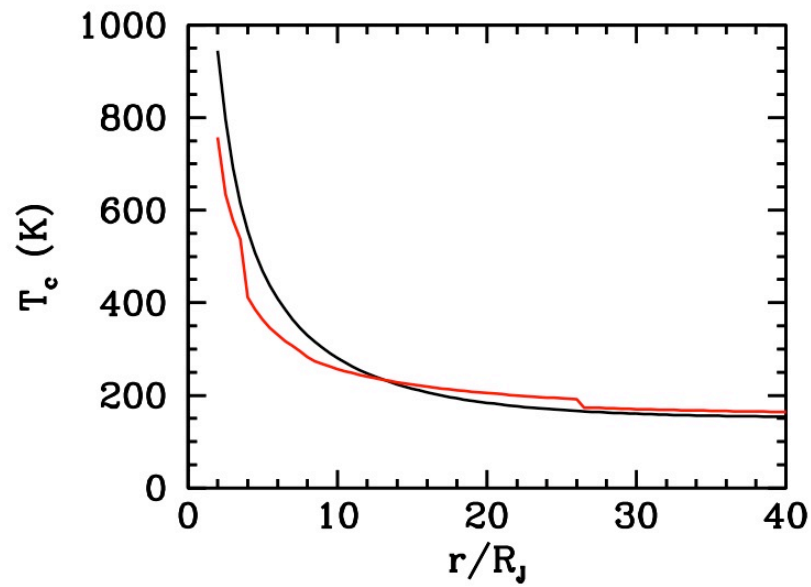
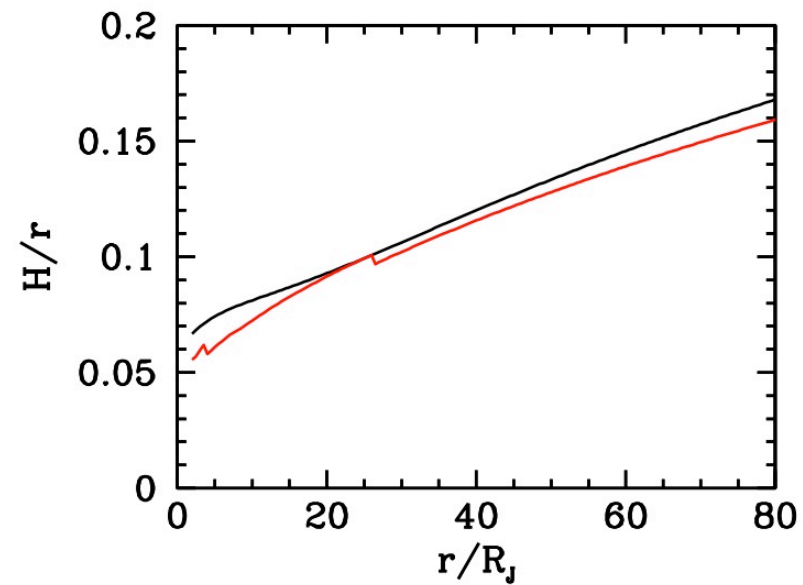
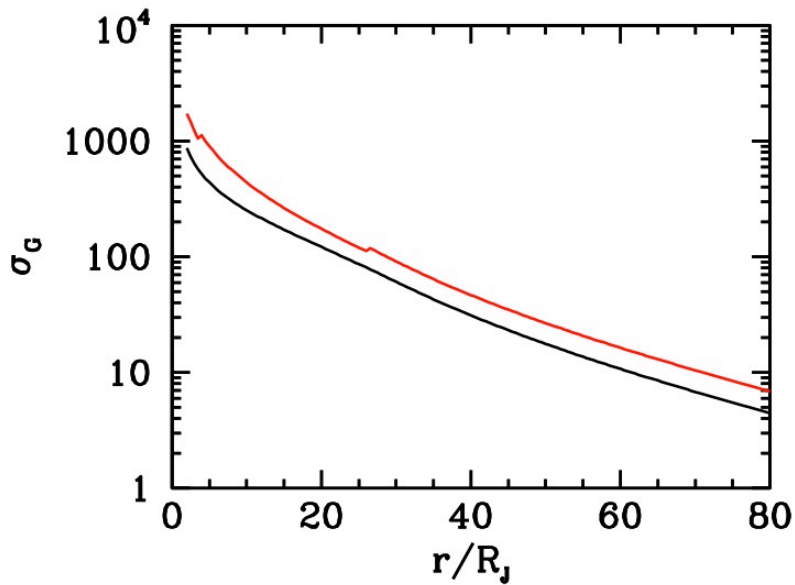
$$f_{\text{opac}} = 1$$

$$\alpha = 5 \times 10^{-3}$$

$$\tau_G = 7 \times 10^7 \text{ yr}$$

Red: Improved gas-starved disk model

Black: CW02 model with $\kappa = f_{\text{opac}}$



- Low opacity model:

$$f_{\text{opac}} = 10^{-4}$$

$$\alpha = 9 \times 10^{-4}$$

$$\tau_G = 2 \times 10^7 \text{ yr}$$

Red: Improved gas-starved disk model

Black: CW02 model with $\kappa = f_{\text{opac}}$

Chemical Network Calculations

- Ionization state from chemical network with gas-phase species H_2 , H_2^+ , Mg , Mg^+ , and e^- after Ilgner & Nelson (2006).

Gas Phase Reactions:

- **Ionization** by interstellar cosmic ray (Umebayashi & Nakano 2009), solar x-ray, and radioisotope decay: $\text{H}_2 \rightarrow \text{H}_2^+ + \text{e}^-$
- **Dissociative Recombination**: $\text{H}_2^+ + \text{e}^- \rightarrow \text{H}_2$
- **Radiative Recombination**: $\text{Mg}^+ + \text{e}^- \rightarrow \text{Mg} + h\nu$
- **Charge Exchange**: $\text{H}_2^+ + \text{Mg} \rightarrow \text{H}_2 + \text{Mg}^+$
- The cosmic ray absorbing column $\approx 96 \text{ g cm}^{-2}$ and x-ray absorbing column $\approx 8 \text{ g cm}^{-2}$.

Grain Surface Reactions:

- Seven species added to reaction network if dust grains are present: Charged grains G^0 , G^\pm , $G^{\pm 2}$ and adsorbed neutrals $H_2(G)$ and $Mg(G)$.
- Thermal adsorption and desorption of neutrals and ions.
- Grain charging and neutralization in collisions with ions and electrons.
- Charge exchange in grain-grain collisions.

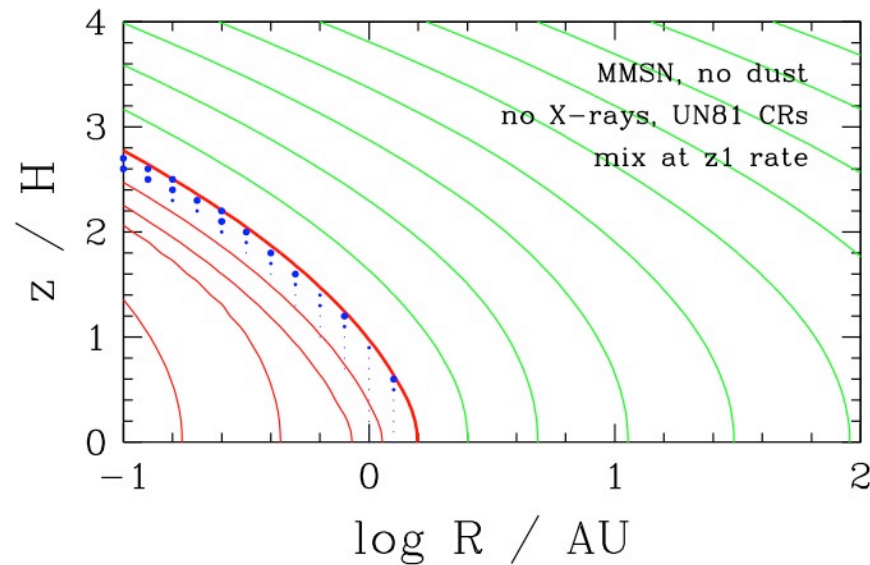
Criteria for Dead Zone

MRI turbulence is absent if both

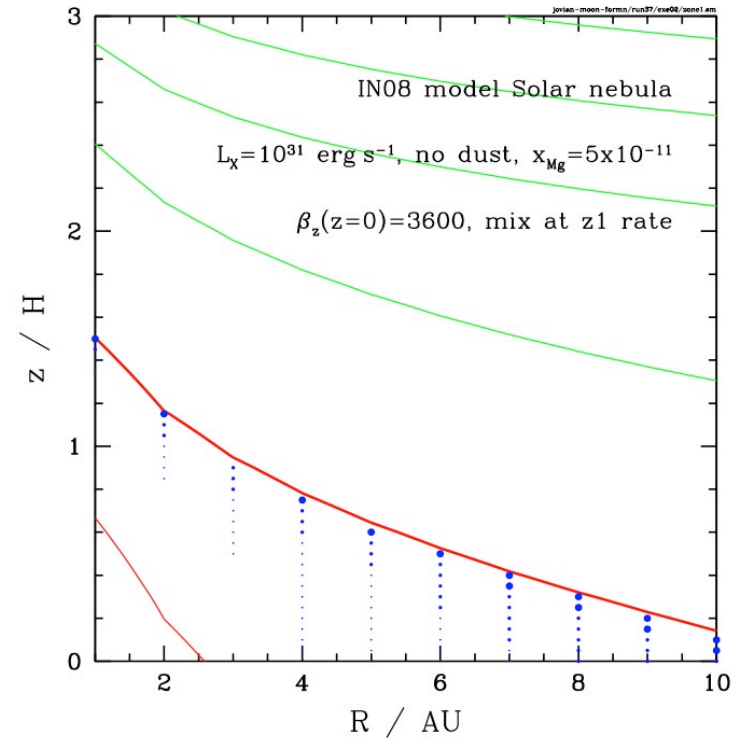
1. The equilibrium ionization is too small (Elsasser number $\Lambda = v_{A,z}^2/(\eta\Omega) < 1$) and
2. The recombination is too fast for ionized gas transported from regions of lower column depth to affect ionization fraction ($t_{\text{rec}} < 0.1 t_{\text{mix}}$).

- The $\Lambda < 1$ criterion was established by previous analytic and numerical results (Jin 1996; Sano & Miyama 1999; Sano & Inutsuka 2001; Sano & Stone 2002).

- The $t_{\text{rec}} < 0.1 t_{\text{mix}}$ criterion from existing MHD+chemistry simulations of the Solar nebula.



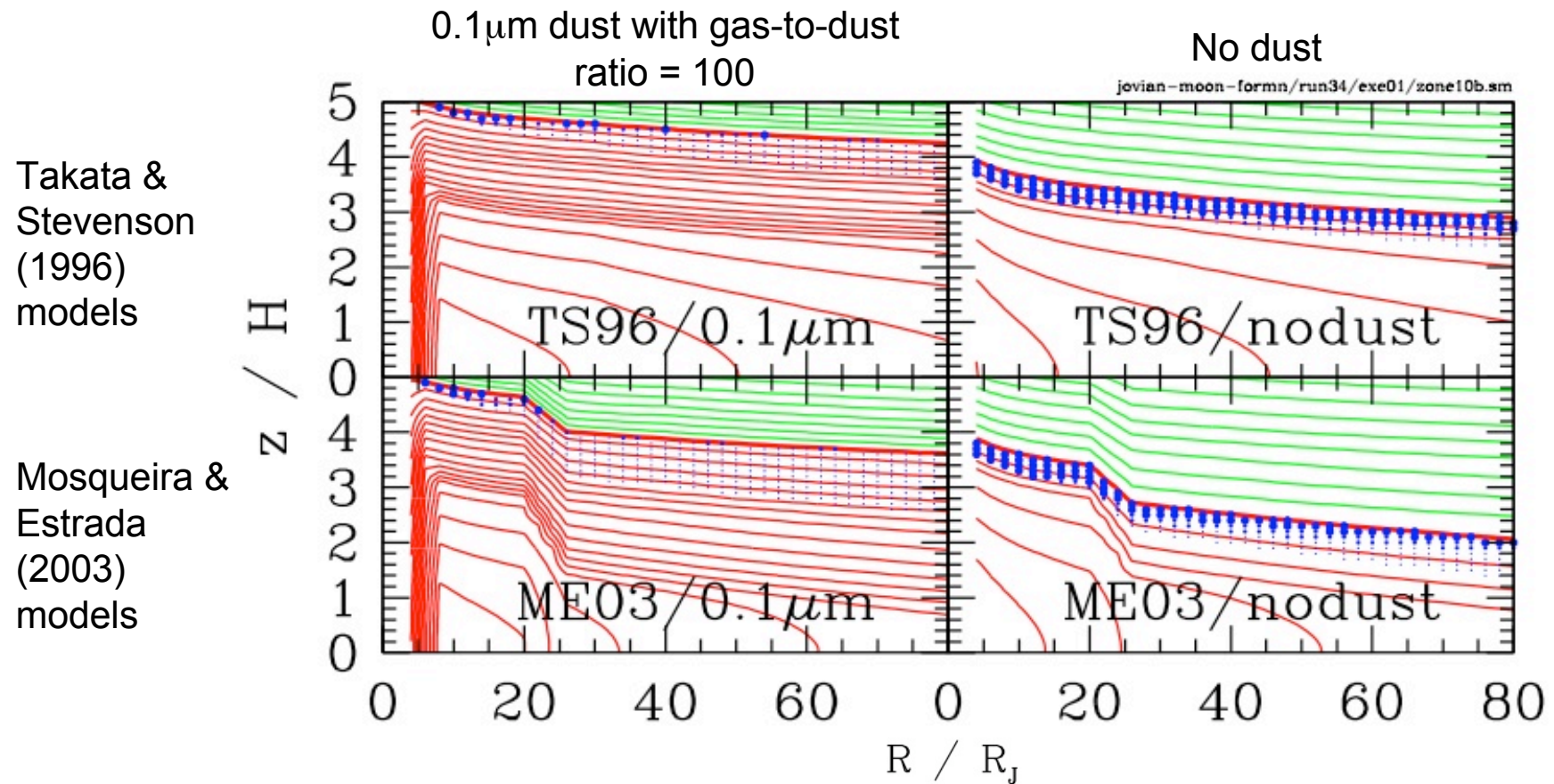
Turner et al. (2007)



Ilgner & Nelson (2008)

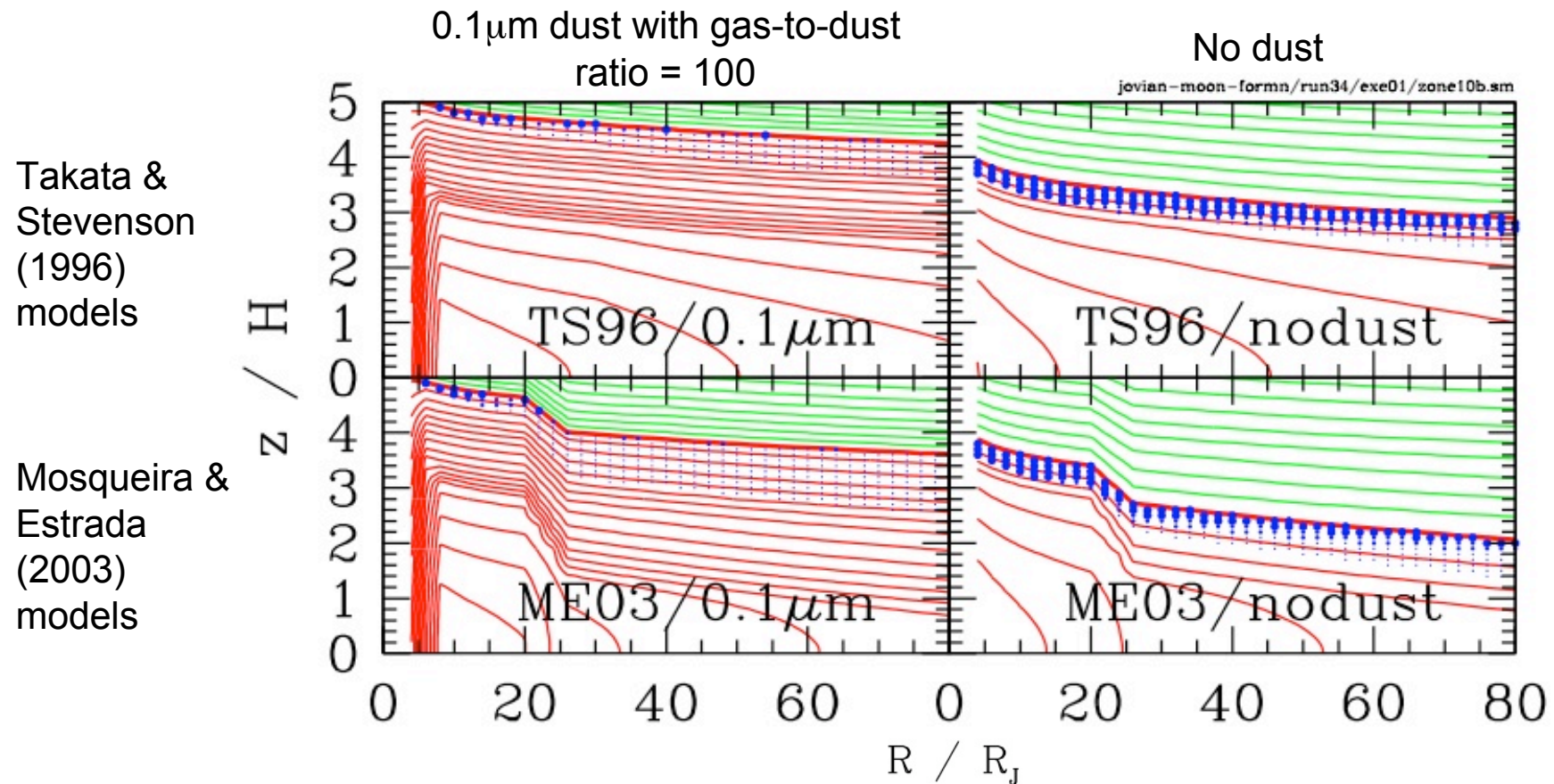
- **Green** contours: $\Lambda > 1$ for equilibrium ionization fraction.
- **Red** contours: $\Lambda < 1$ for equilibrium ionization fraction.
- Large **blue** dots: $t_{\text{rec}} > t_{\text{mix}}$
- Medium **blue** dots: $t_{\text{mix}} > t_{\text{rec}} > 0.1 t_{\text{mix}}$

Dead Zone of Minimum Mass Subnebula



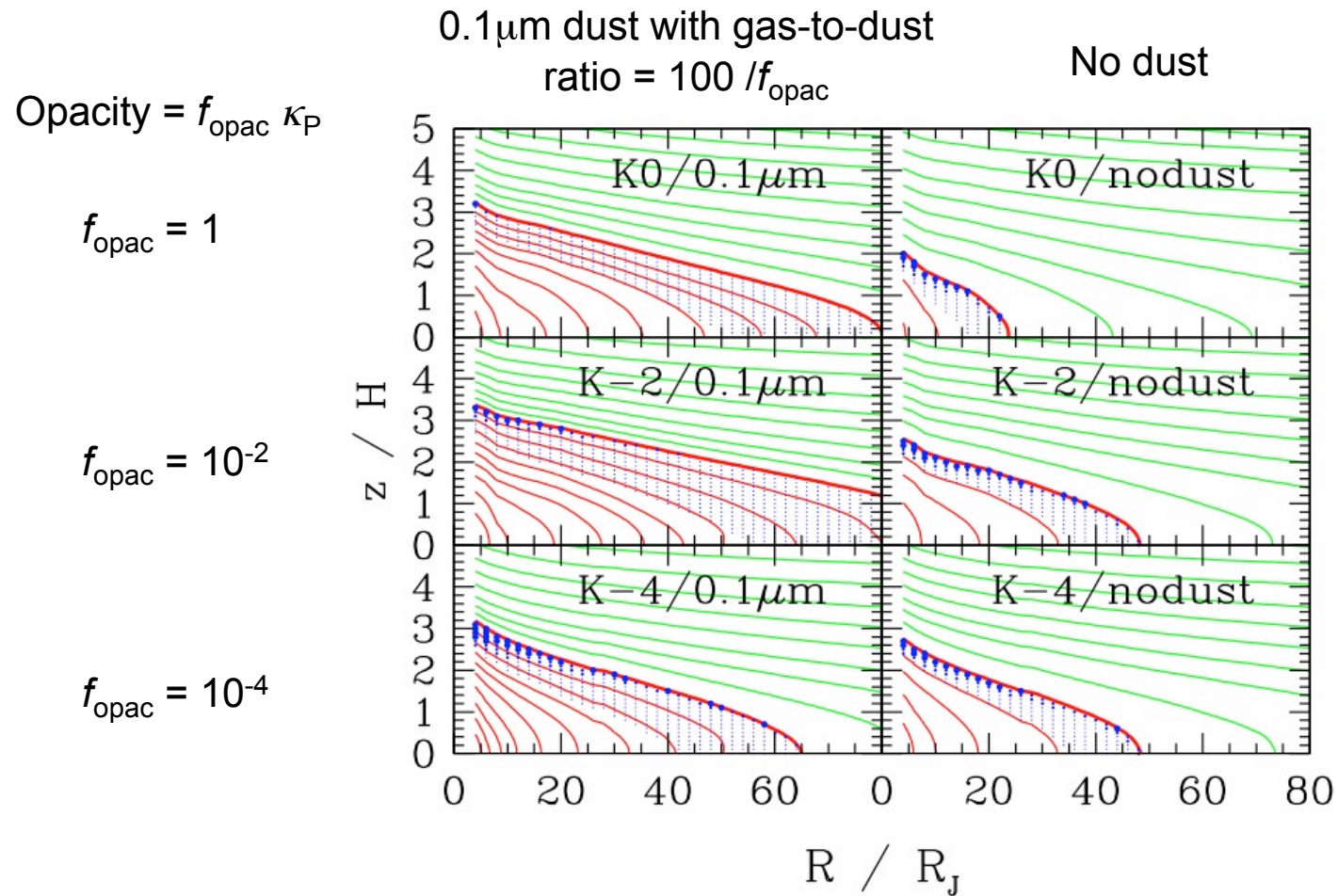
- Mixing can slightly reduce the size of the dead zone if there is no dust.

Dead Zone of Minimum Mass Subnebula



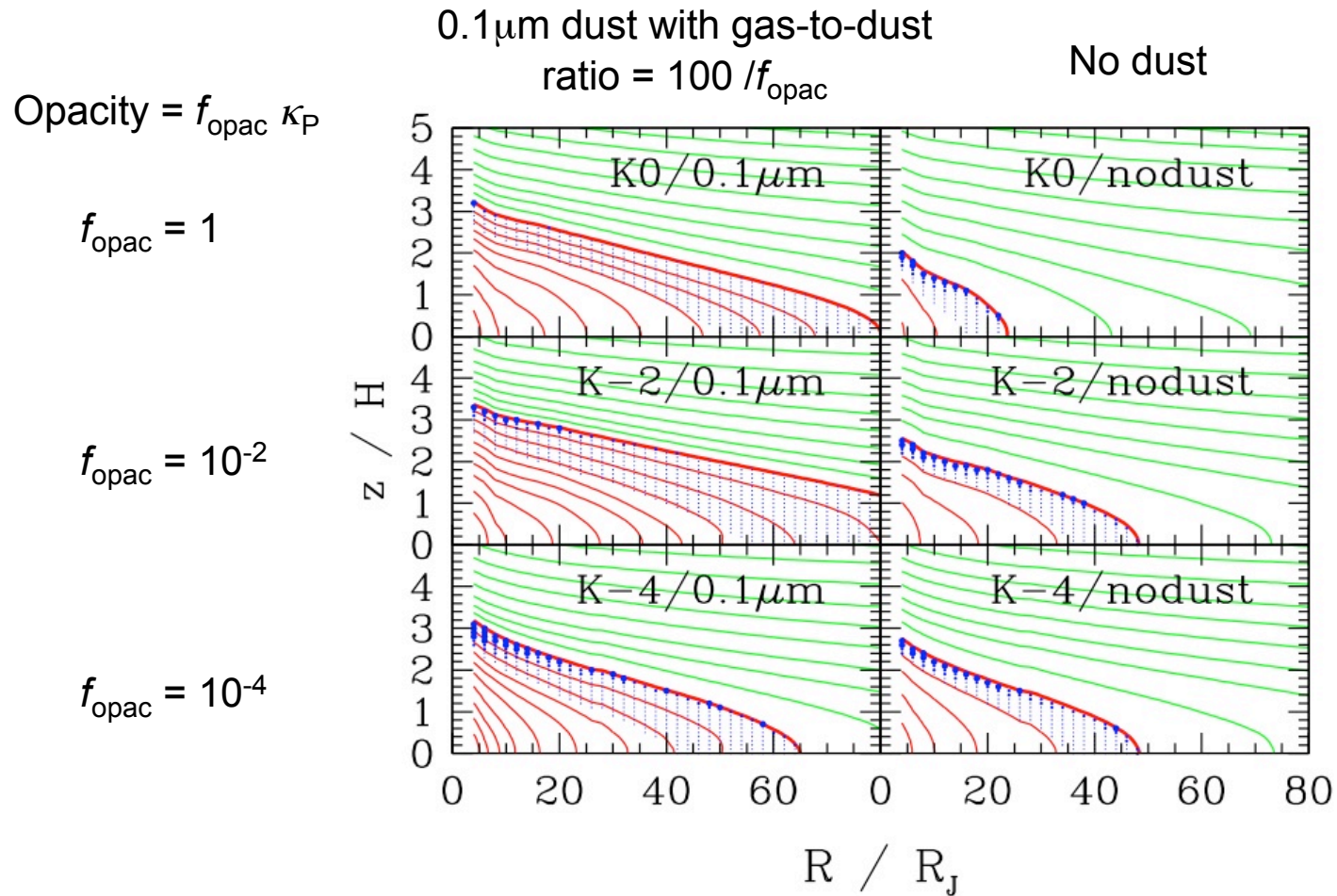
- Even with the sharp drop in surface density at $r/R_J \approx 23$ in the Mosqueira & Estrada models, MMSN models are magnetically dead everywhere, except very high in the upper layers.

Dead Zone of Gas-Starved Subnebula



- Mixing does not significantly affect the size of the dead zone.

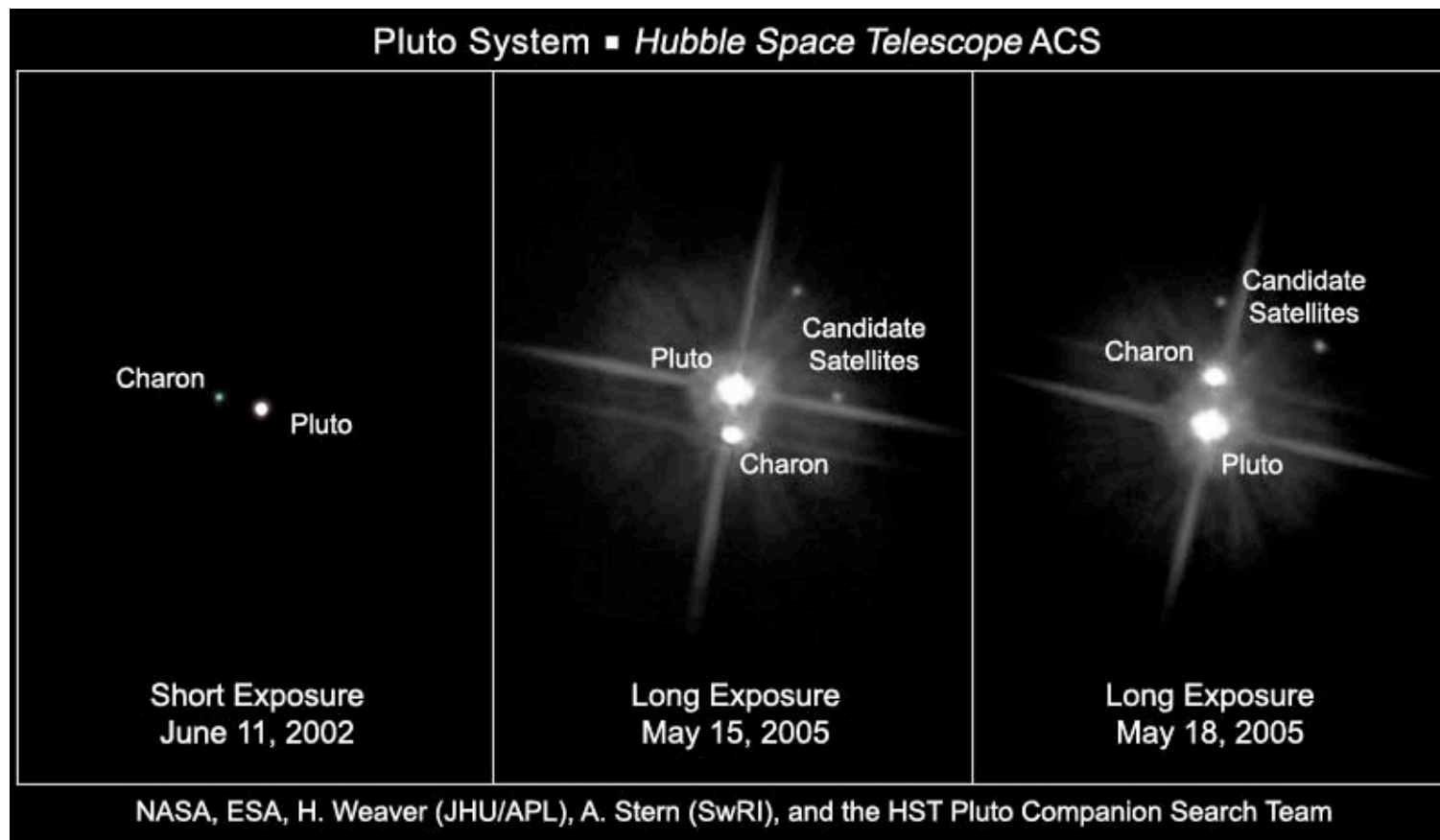
Dead Zone of Gas-Starved Subnebula



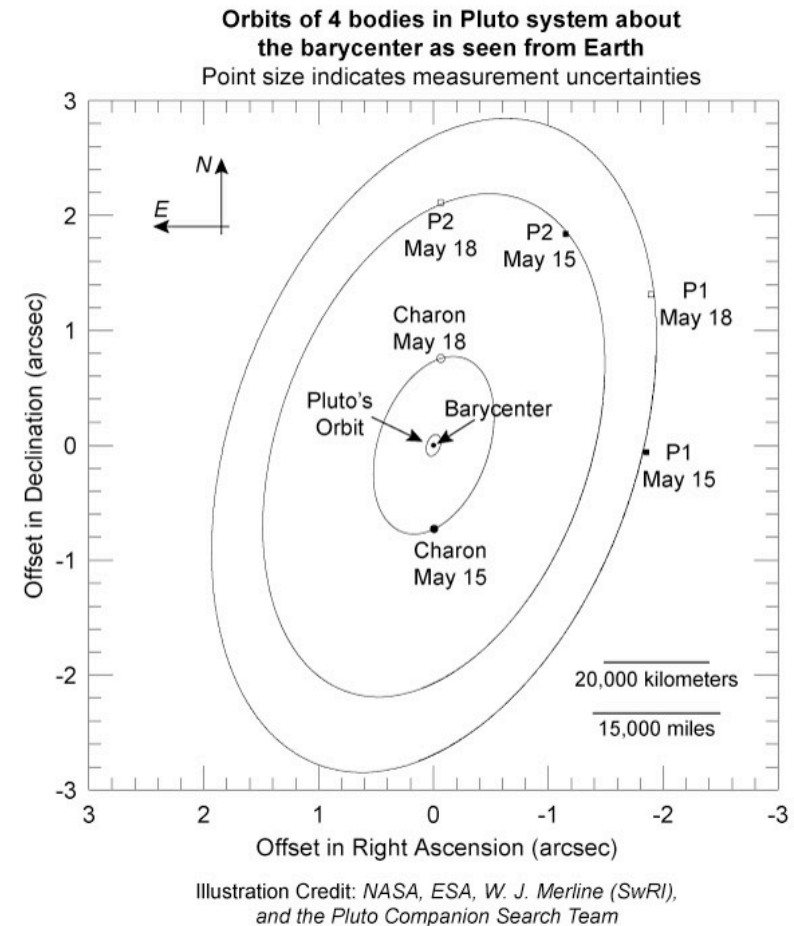
- No dead zone in the outer regions.
- Dead zone plus active upper layers in the inner regions.

Pluto Satellite System

- Charon was discovered in 1978.
- Two small satellites, Nix and Hydra, were discovered in 2005 by Weaver et al.

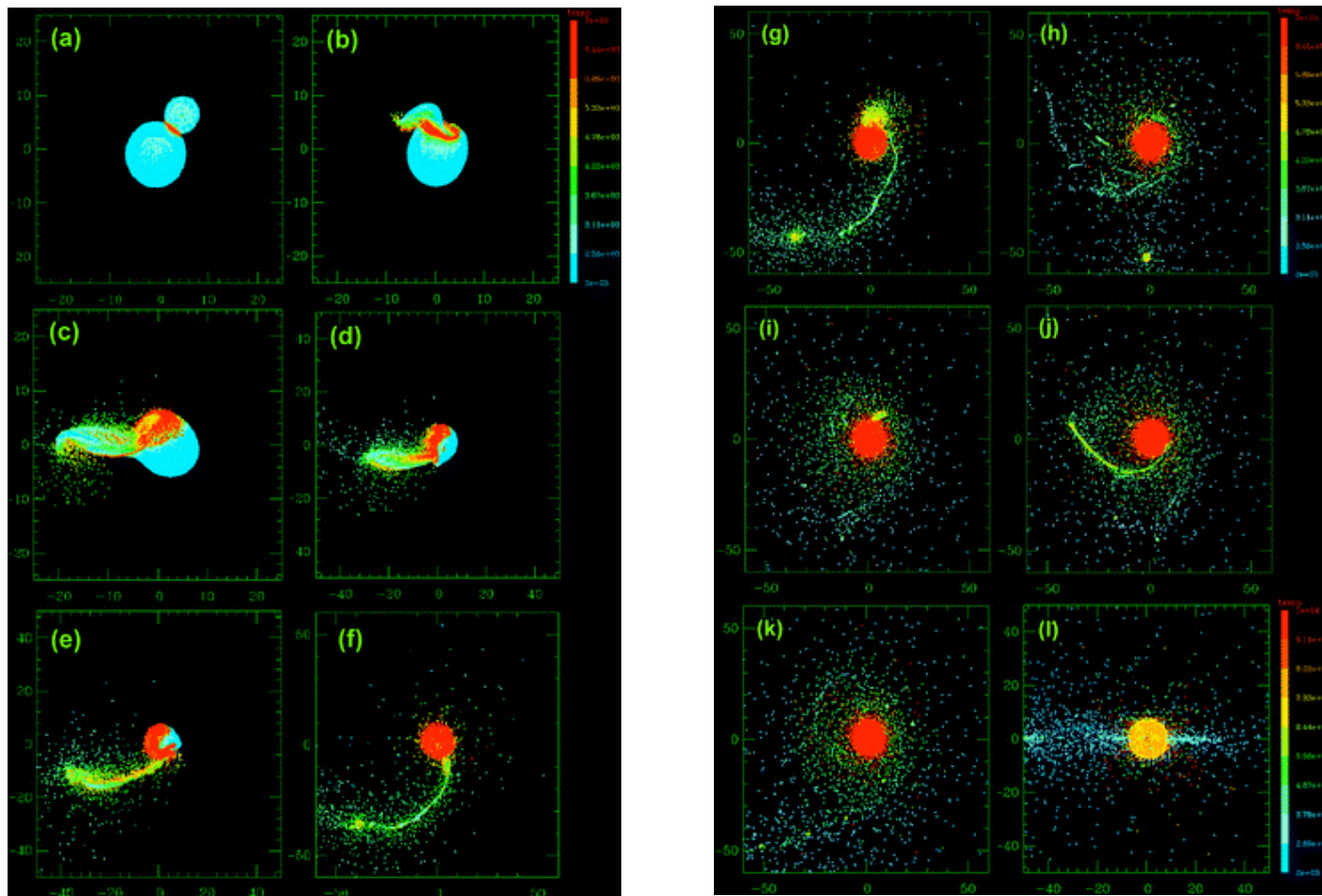


- Orbits of Nix and Hydra nearly circular and nearly coplanar with that of Pluto-Charon (Buie et al. 2006).
- Orbital periods of Charon, Nix and Hydra nearly in the ratio 1:4:6.
- Orbits of Nix and Hydra significantly non-Keplerian due to
 - large mass ratio of Charon-Pluto
 - proximity of Nix and Hydra to 3:2 commensurability
 (Lee & Peale 2006).



Giant Impact Origin of the Moon

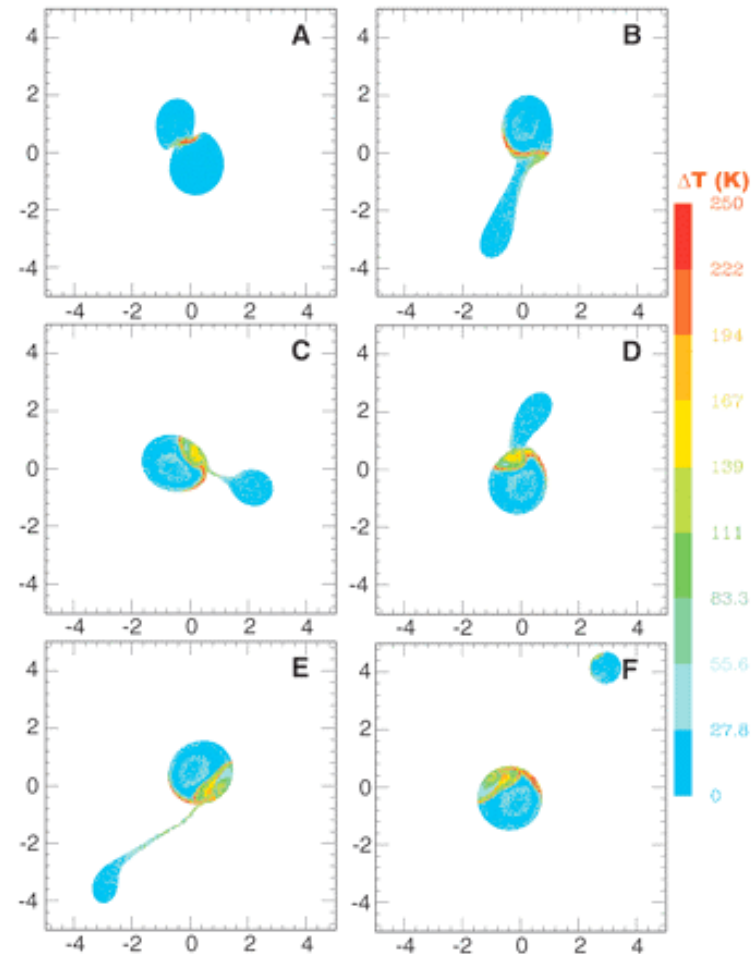
- Moon accreted from impact generated disk.



(Canup 2004)

Impact Origin of the Pluto Satellite System

- Impact captured Charon nearly intact into eccentric orbit with $a_c \sim 4 R_p$.
- Coplanarity: Nix and Hydra were debris from the same impact.
- But debris did not extend beyond $\sim 15 R_p$.
- Current $a = 17, 42$, and $56 R_p$ for Charon, Nix, and Hydra.



(Canup 2005)

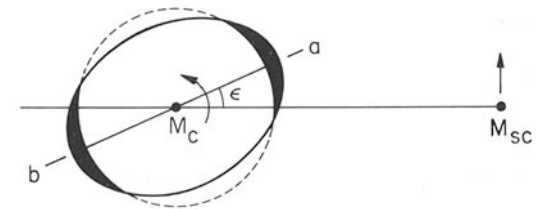
Resonant Migration of Nix and Hydra

- Nix and Hydra not in 4:1 and 6:1 resonances with Charon at present.
- But Nix and Hydra could once be in these resonances and were pushed out as Charon's orbit expanded due to tidal evolution (Ward & Canup 2006).

- Stable transport of Nix and Hydra in 4:1 and 6:1 as a_c increases by a factor of ~ 4 is difficult:
 - Ward & Canup (2006): Nix and Hydra trapped in corotation resonance only , which does not excite eccentricity.
 - Charon's eccentricity e_c must be maintained during most of the orbital expansion to maintain stability of resonance.
 - Lithwick & Wu (2007):
 - To transport Nix, $e_c < \sim 0.024$
 - To transport Hydra, $e_c > \sim 0.8 R_p/a_c$
 - Both cannot be satisfied at the same time.

Tidal Evolution of Pluto-Charon

- Need evolution of Charon's orbit (in particular e_c) for resonant migration problem.
- Previous study of tidal evolution of Charon's orbit assumed circular orbit (Dobrovolskis et al. 1997).
- Tidal Models:
 - Constant time lag Δt : closed expressions valid for large e (Mignard 1980; Hut 1981).
 - Constant dissipation function Q (Goldreich & Soter 1966)
 - Tides on both Pluto and Charon
 - Non-zero $C_{22} = (B-A)/(4MR^2)$: Permanent non-axisymmetric deformation



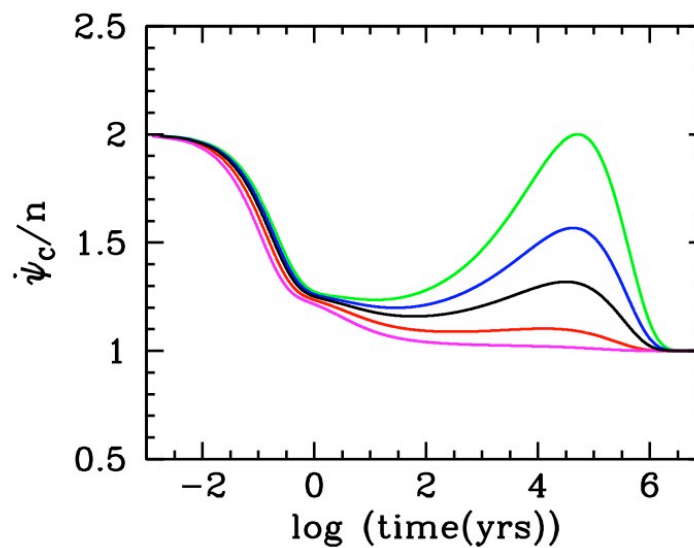
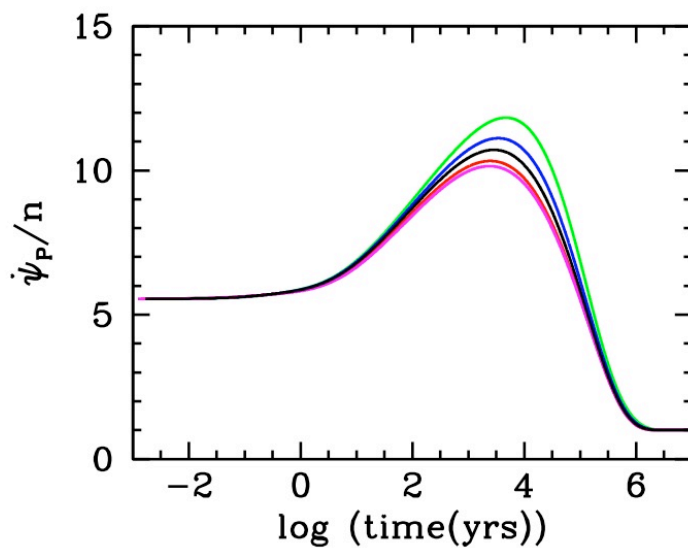
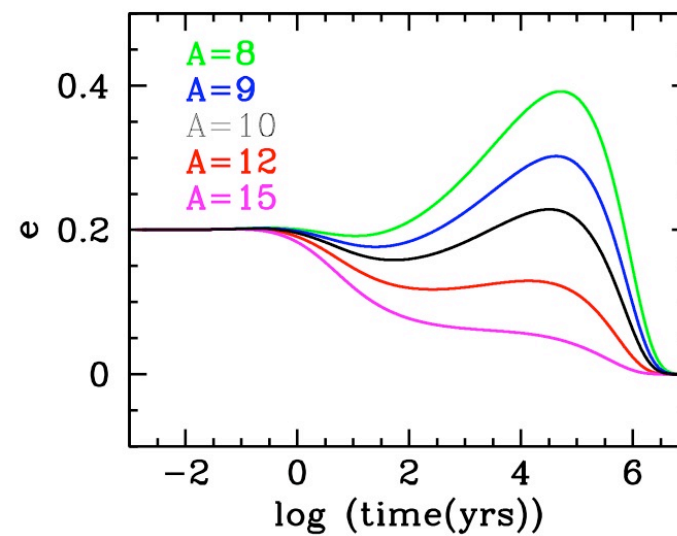
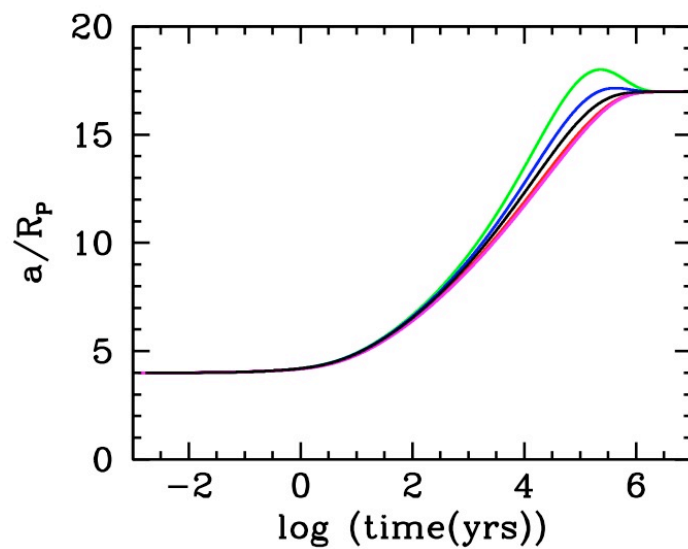
$$\begin{aligned}\frac{1}{n} \left\langle \frac{d\dot{\psi}_i}{dt} \right\rangle &= \frac{3G}{C_i a^6} k_{2i} \Delta t_i M_j^2 R_i^5 \left[f_1(e^2) - f_2(e^2) \frac{\dot{\psi}_i}{n} \right], \\ \frac{1}{a} \left\langle \frac{da}{dt} \right\rangle &= \frac{6G}{\mu a^8} k_{2P} \Delta t_P M_C^2 R_P^5 \left\{ \left[\frac{\dot{\psi}_P}{n} f_1(e^2) - f_3(e^2) \right] + A \left[\frac{\dot{\psi}_C}{n} f_1(e^2) - f_3(e^2) \right] \right\}, \\ \frac{1}{e} \left\langle \frac{de}{dt} \right\rangle &= \frac{27G}{\mu a^8} k_{2P} \Delta t_P M_C^2 R_P^5 \left\{ \left[\frac{11}{18} \frac{\dot{\psi}_P}{n} f_4(e^2) - f_5(e^2) \right] + A \left[\frac{11}{18} \frac{\dot{\psi}_C}{n} f_4(e^2) - f_5(e^2) \right] \right\};\end{aligned}$$

where

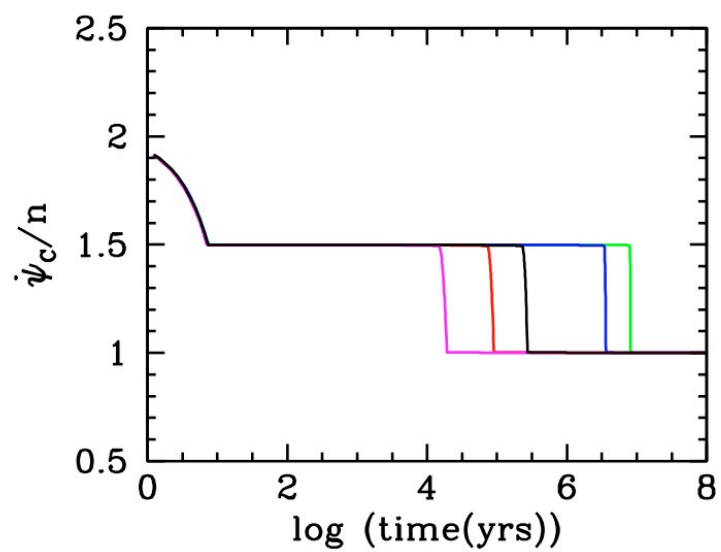
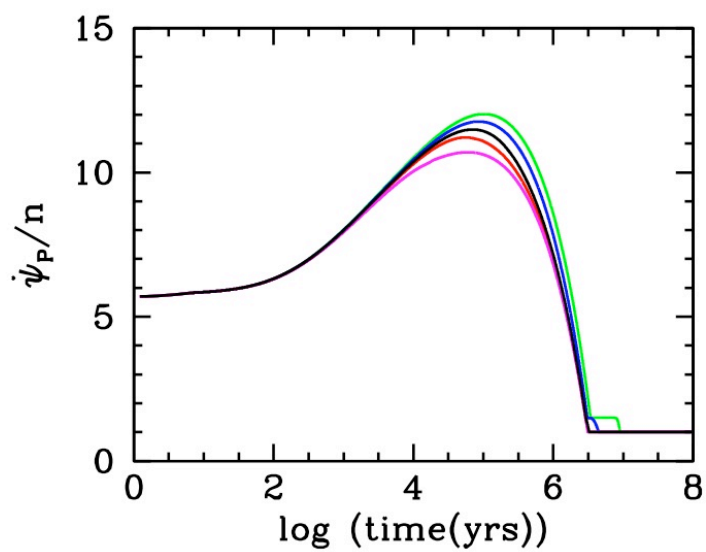
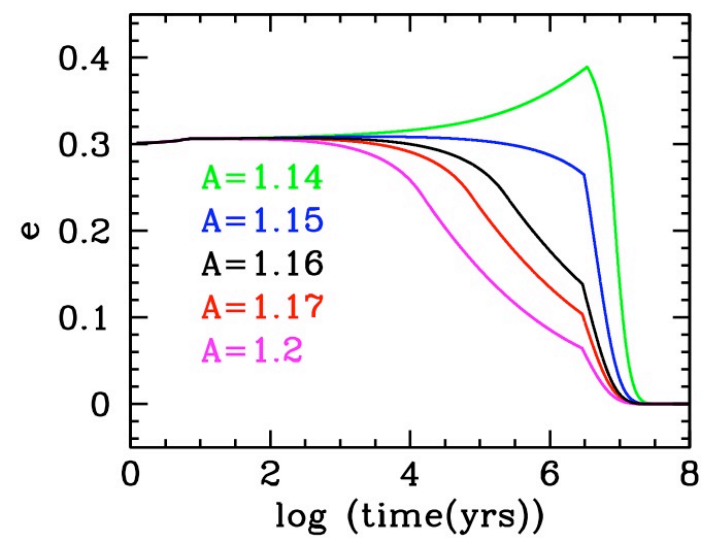
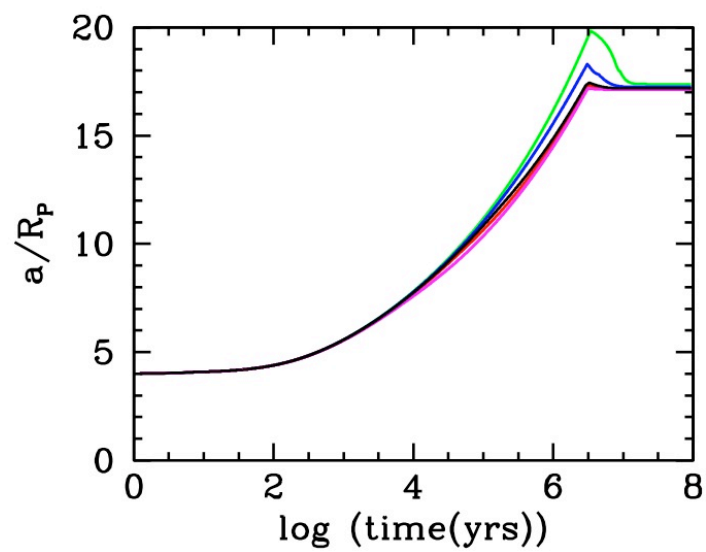
$$A = \frac{k_{2C}}{k_{2P}} \frac{\Delta t_C}{\Delta t_P} \left(\frac{M_P}{M_C} \right)^2 \left(\frac{R_C}{R_P} \right)^5$$

- $A \approx (\mu_p \Delta t_c R_c)/(\mu_c \Delta t_p R_p)$ is a measure of relative rates of tidal dissipation.

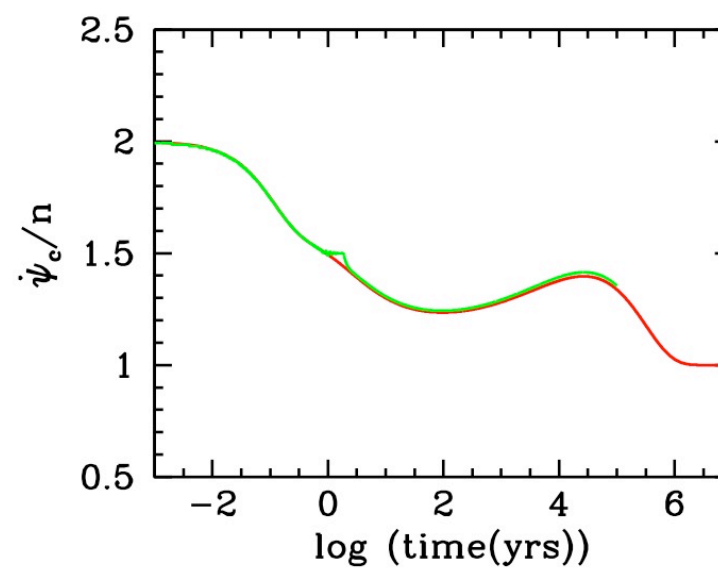
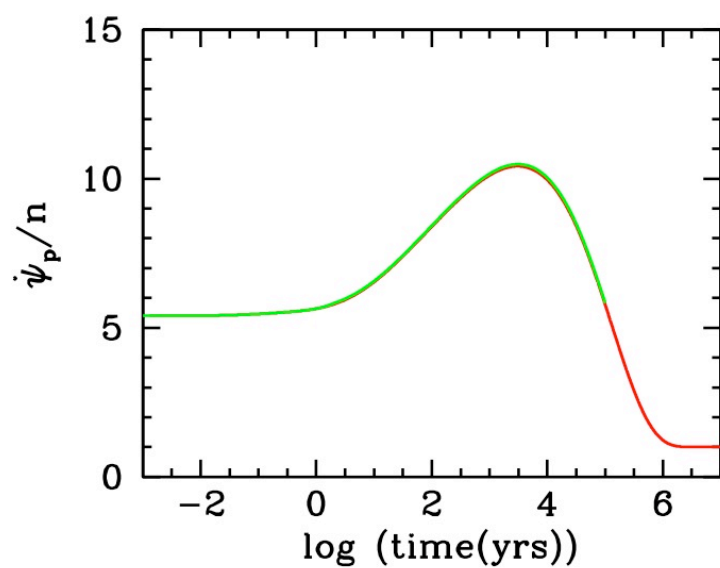
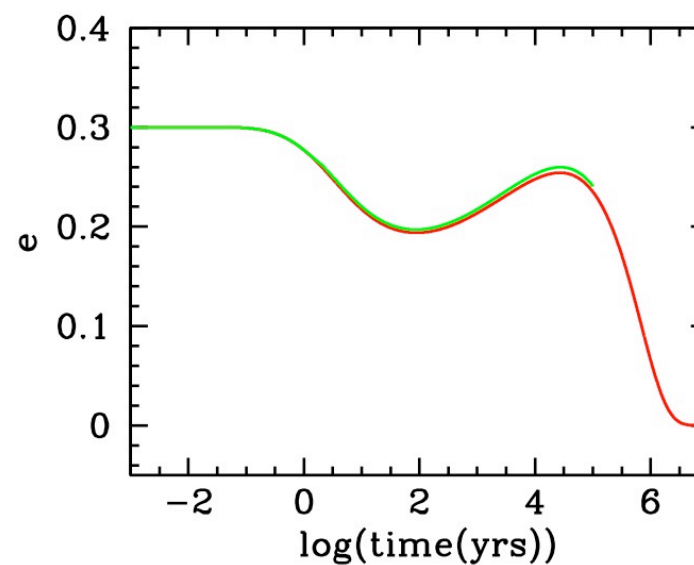
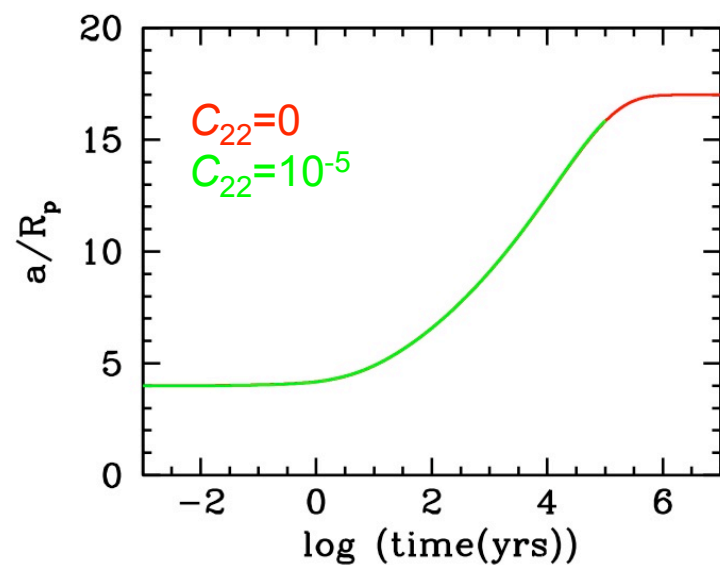
$$k_{2p} = 0.058, \Delta t_p = 10 \text{ mins}$$



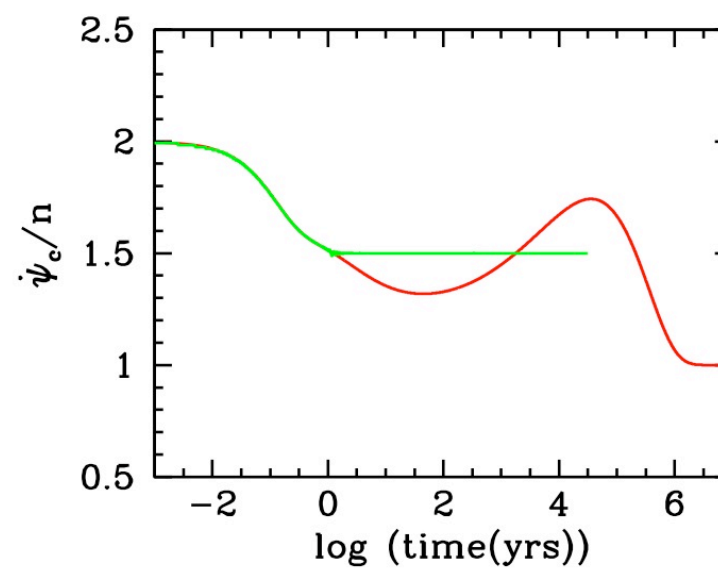
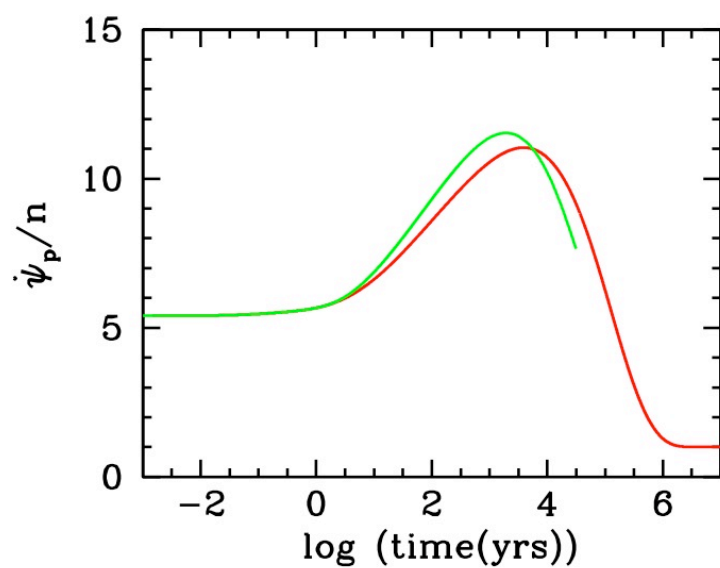
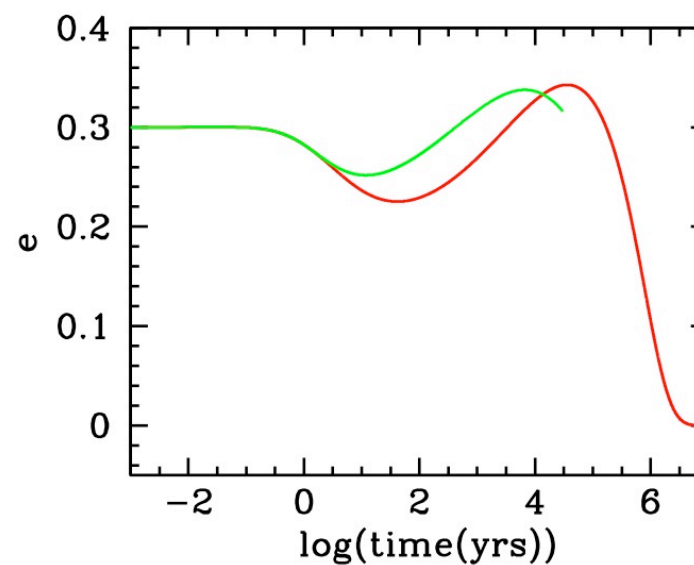
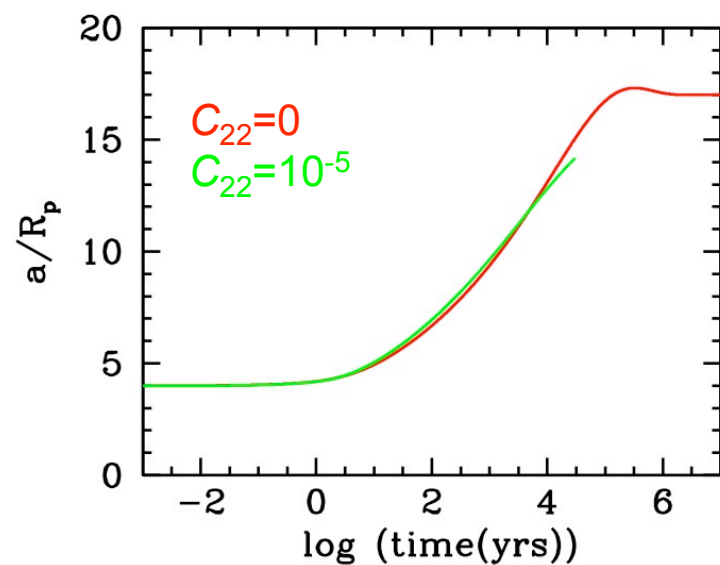
$$k_{2p} = 0.058, Q = 100$$



$$k_{2p} = 0.058, \Delta t_p = 10 \text{ mins}, A = 10$$



$$k_{2p} = 0.058, \Delta t_p = 10 \text{ mins}, A = 9$$



Summary (I)

- We have developed criteria for estimating the size of the dead zone from chemical network calculations.
- Minimum Mass Subnebula models of the circumjovian disk are magnetically dead everywhere, except very high in the upper layers.
- Gas-starved Subnebula models are similar to solar nebula models:
 - No dead zone in the outer regions
 - Dead zone plus active upper layers in the inner regions.

Summary (II)

- Tidal evolution of Pluto-Charon shows complex behaviors: pseudo-synchronous rotation, 3:2 spin-orbit resonance, semimajor axis overshooting
- Can a consistent history of the Pluto satellite system be constructed based on intact capture of Charon and resonant migration of Nix and Hydra?